QUATERNARY FACIES ASSEMBLAGES AND THEIR BOUNDING SURFACES, CHESAPEAKE BAY MOUTH: AN APPROACH TO MESOSCALE STRATIGRAPHIC ANALYSIS

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ABSTRACT: **Shallow marine facies assemblages in the late Quaternary section of Virginia's Eastern Shore Peninsula shed new light on the relationship between mesoscale stratigraphic units (facies assemblages or ''depositional systems'') and the bounding surfaces from which they have been formed. These units were deposited by the coast-parallel progradation of the Pleistocene barrier spit (Eastern Shore Peninsula) during successive highstands. As a consequence, each segment of the spit complex has been produced by the coast-parallel translation of a relatively small growth area at the spit tip. The distal end of the present (Holocene) barrier system appears to closely resemble the Pleistocene highstand growth area, and this environment consequently serves as a partial analog for interpreting the depositional environment of the fossil highstand deposits.**

The many facies patterns present in the spit complex can be reduced to four kinds of facies assemblages (depositional systems), adopting a process-based model (facies template). In this scheme, definitions of both ''facies'' and ''facies assemblage'' are more limited than is the case in most textbook definitions in that the facies of a given assemblage are systematically related to each other by grain size and stratal pattern, and also related to a bounding surface (''source diastem'') which is the immediate source of sediment for the facies assemblage. Vertical transitions between individual facies are easily identified in outcrop, but the horizontal gradients of facies change are too gentle to be observed over the short dimensions of the borrow pits, and do not have sufficient acoustic contrast to appear on ground-penetrating radar records. However, the facies assemblages, both in the borrow pits and on radar records, stand out by virtue of their sharply defined bounding surfaces (source diastems). The facies assemblage either buries its source diastem or is capped by it.

The assemblages in the spit complex are, in ascending stratigraphic order: (1) several tidal shoal assemblages, each underlain by a channel-base diastem, (2) Two shoreface assemblages separated by an intervening marginal shoal assemblage and its underlying channel-base diastem, and (3) a beach-strandplain assemblage, underlain by a surf diastem. All of these systems prograded southward as the nose of the spit prograded, and while they did so, zones of erosion cut the bounding surfaces that separate them. Two important bounding surfaces are ''conjugate'' surfaces, that nourished both the facies assemblage above and the assemblage beneath. As each surface advanced, erosion at their leading edge spilled sediment forward, down the nose of the spit, while sediment was also swept backward, aiding in the burial of the surface. A conjugate surface creates a ''sandwich'' structure, in which two facies assemblages are separated by the generating surface. Proximal facies are back-to-back across these sediment-spreading boundaries.

Episodic progradation of the spit tip by development of successive, recurved, beach ridges has overprinted the horizontal first-order reflectors (separating facies assemblages) with gently dipping second-order reflectors that separate successive growth increments of the spit. Although less clearly defined, these growth increments are essentially high-frequency autocyclic sequences, and constitute the next higher scale of spatial organization above the depositional systems scale. The manner in which facies have been organized into depositional systems in the late Pleistocene highstand deposits of the Eastern Shore is specific to this estuary-mouth setting. These assemblages are, however, local expressions of a facies ''template'' that can be generalized to many other settings.

INTRODUCTION

Modern stratigraphy assumes a hierarchical spatial organization. Small-scale stratigraphy is defined by sedimentological concepts (beds, bed sets, and bed cosets; McKee and Weir 1953; Campbell 1967). At larger spatial scales stratigraphy is defined by sequence concepts (systems tracts, parasequences, sequences; Vail et al. 1977 and many later papers). Between these end members is an intermediate region, described by the plastic term ''facies'' (See Hedberg 1976, for a history of the word). In this paper, we use the Quaternary section of Chesapeake Bay mouth as a laboratory in which to examine mesoscale stratigraphy in a shallow marine setting and develop generalizations concerning its nature.

The Quaternary of the Eastern Shore Peninsula is an ideal location for studying mesoscale stratigraphy (Fig. 1). Outcrops and water wells on land reveal stratigraphy at intermediate scales; some are sensed by sophisticated wire-line logging systems. The excellent acoustic coupling of the water column and seabed on the adjacent shelf has been exploited for geophysical investigations at intermediate scales by several workers (e.g., Foyle and Oertel 1997), and the advent of ground-penetrating radar (GPR) now allows a similar resolution on land. Furthermore, the dispersal systems that have generated the Quaternary stratigraphy are still operating.

Our analysis of the Quaternary of Chesapeake Bay Mouth begins with the presentation of a simple model (genetic facies model) for intermediate-scale stratigraphy that will allow us to organize our observations. The Eastern Shore study area and its present (Holocene) dispersal systems are described. We then outline the late Pleistocene stratigraphic section and show how the Holocene dispersal systems can be fitted to the genetic facies model to produce a ''facies template'' that matches our observations of the Pleistocene section.

Conceptual Model for Granulometric Facies Assemblages

Facies, the commonly recognized mesoscale unit, has been defined by Reading (1996) as a ''sedimentary volume of constant character.'' The studies described here have led us to conclude that intermediate-scale lithologic units (facies bodies) are not randomly distributed within stratigraphic bodies. Walther's law (Walther 1874, in Middleton 1973) says as much, but we suggest a more limited relationship in which a small number of spatial arrangements (facies assemblages or depositional systems) are bounded by surfaces to which they are genetically related (Swift et al. 2003). These assemblages are constructed in a systematic way from small-scale units (beds and bed sets). They can be mapped and systematically related to the larger-scale units of sequence stratigraphy. In order to test this hypothesis against the Quaternary of Chesapeake Bay Mouth, we present a more limited definition of lithology-defined facies (lithofacies). *Granulometric facies* are a variant of lithofacies, defined by large-scale,

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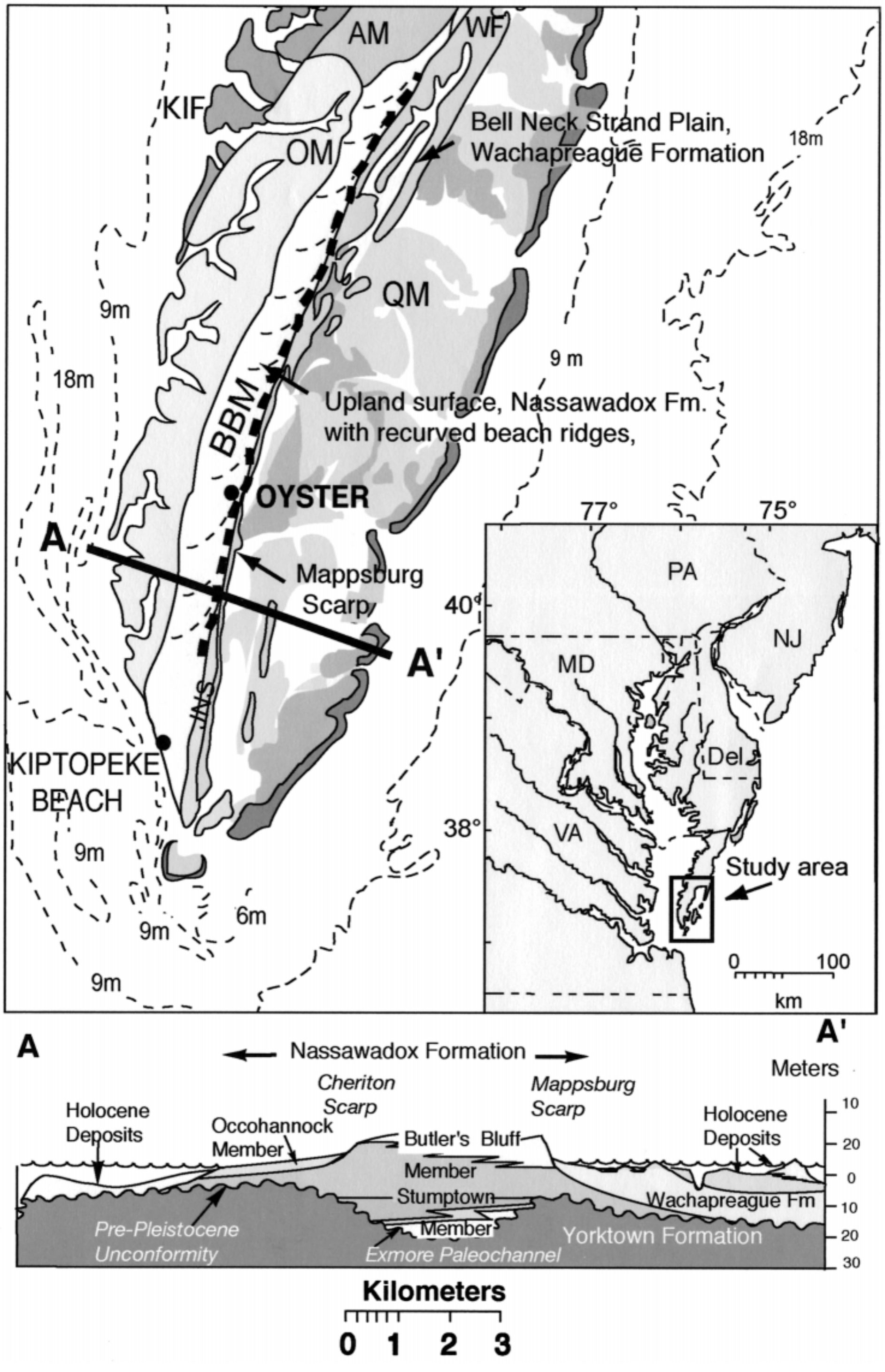

FIG. 1.—Geologic Map of the late Pleistocene deposits of the southern part of the Eastern Shore Peninsula of Virginia, after Mixon (1985) with the Kiptopeke Beach, Oyster, and Mappsville localities indicated. The upper surface of the Butlers Bluff Member of the Nassawadox Formation constitutes the Upland Surface of Mixon (1985), and the upper surface of the Wachapreague Formation constitutes his Bell Neck Strand plain. The Mappsburg Scarp separates the two surfaces. AM = Accomack Member of the Omar Formation, KIF = Kent Island Formation, OM = Occohannock Member, WF = Wachapreague Formation, BBM = Butlers Bluff Member, QM = Quaternary coastal deposits. Note Mappsville and Cheriton Scarps, marking the 125,000 yr highstand. The Stumptown Member of the Nassawadox Formation, with its several ''facies'' described by Mixon (1985), is an entirely subsurface unit, lying within the Eastville Paleochannel.

horizontal grain-size gradients (meters or kilometers; ''facies change'') and small-scale, cyclic, vertical grain-size variation (millimeters to centimeters; ''stratification''). See Swift et al. (2003) for a more complete discussion of the granulometric facies concept. Our granulometric facies model adds several new terms to an already complex technical vocabulary; however, our observations of Quaternary coastal deposits require the concepts that these terms represent.

In the model (Fig. 2), the sea floor is a *dispersal system.* A dispersal system can be defined as an assemblage of flow-linked dispersal environments aligned along a gradient of decreasing time-averaged fluid power, which is also a gradient in transport competence and capacity (Swift et al. 1991). We assume that the dispersal system consists of an initial zone of flow acceleration, followed by a series of zones of flow deceleration. The zone of flow acceleration is the most proximal environment of the dispersal system and is the eroding *source environment.* The zones of flow deceleration are successive dispersal environments that are partial sinks, bypassing successively finer fractions of the transported load to downstream environments. The two-dimensional dispersal system generates a three-di-

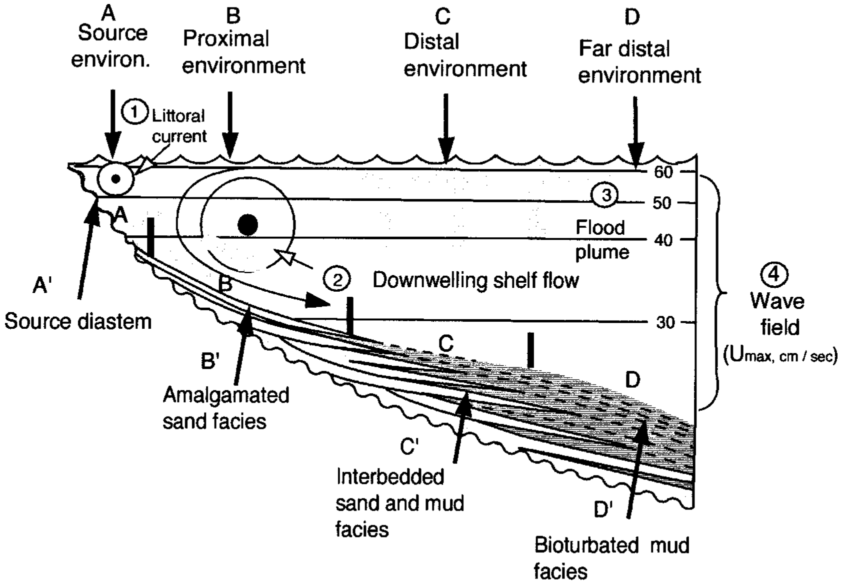

FIG. 2.—''Depositional systems template,'' configured for a transgressive shoreface–shelf setting. 1–4: Dispersal mechanisms. A–D: successive environments of the dispersal system. A′–D′: Corresponding facies of the depositional system. Note the onlapping, backstepping geometry of the beds and the landward and downward increase in stratal condensation (decrease in bed count per unit thickness of succession).

mensional *depositional system* as the basin subsides, and the rising, shifting, depositional surfaces generate facies volumes.

The generalized model for a depositional system sketched above (Fig. 2) is a guide or *template* to stress the fact that its critical elements (mechanisms, environments, facies) can be fitted to a variety of depositional settings, with consequent modifications to its geometry. For instance, in Figure 2 the template is configured for a transgressive shelf setting. Dispersal mechanisms (1–4) move sediment from the source environment through a series of dispersal environments (A–D). As sea level rises, the dispersal environments rise and shift landward, creating the volumes that become the corresponding facies (A′–D′). However, the source environment is an erosional rather than a depositional environment. Its trajectory does not generate a facies volume, but instead cuts a bounding surface, or *source diastem.* In this transgressive setting, the facies succession fines upwards, with the distal and far-distal facies overlying the proximal facies. In this simplified drawing, the degree of stratal condensation varies with height above the source diastem; the bed count per unit depth in the section, when traced seaward, first increases, then decreases (e.g., Aigner and Reineck 1984). The landward beds are the thin, coarse, eroded bases of long-return-period storm beds (Zhang et al. 1997). They are succeeded by finer but thicker beds that were deposited in deeper water and have thus experienced less erosion during the burial process. These are overlain by yet finer beds that were deposited in a more seaward setting with reduced sediment supply. There is little erosion, but the beds are sediment-starved, so are thinner. The source diastem is in this case a *ravinement* (unconformity cut by a transgressing sea; Stamp 1922, in Swift 1967). It is a source diastem because it is the immediate source for the sediment in the depositional system.

The depositional system illustrated in Figure 2 is an open one in that the depositional system is not yet complete, i.e., the lower bounding surface is a ravinement surface, but the upper bounding surface is still the aggrading sea floor. However, should sediment supply exceed accommodation (regressive setting), the succession is reversed (Fig. 3A). Instead of shifting landward, cutting the basal ravinement, and being buried by its own debris, the source environment (surf zone) shifts seaward and truncates the section that it is depositing. Proximal, distal, and far-distal facies are stacked in reverse (downward fining) order beneath the source diastem. The source diastem (in this case, a *surf diastem*) is only exposed as its leading edge is created during the peak of storm erosion. The resulting strip of surface is buried as the storm wanes, and a new strip is created by the next major event. In cores through prograding shorefaces, the surf diastem is identified as the basal surface of the lowest high-angle cross-strata set. As with the ravinement, the surf diastem is a source diastem because it is the immediate source for sediment in the depositional system. Sediment delivered to a prograding shoreface may have come from a nearby river mouth, but it was delivered by the wave-driven littoral current, and its most recent resting place was the adjacent surf zone (source environment).

In a figure such as Figure 3B, the trajectory of each grain, from the source diastem to its burial position, can be projected onto the plane of the diagram as the trace of a bedding plane. As such, it constitutes a time line. Comparison of grain trajectories on opposite sides of bounding surfaces reveals two main classes: divergent boundaries (erosional), and convergent boundaries (depositional; see Fig. 3B). In the example of Figure 3B, the source diastem is a convergent boundary, and it is also a conjugate boundary in that it has simultaneously nourished two seaward-prograding dispersal systems: one above it and one below it.

In this discussion, we use the term ''depositional system'' as originally defined by Fisher and McGowen (1967), ''an assemblage of genetically related facies.'' We use the equivalent term ''facies assemblage'' for a mesoscale unit when we wish to stress the component facies lying between its bounding surfaces, and we use the term ''depositional system'' when we wish to stress the parallelism between this intermediate scale of organization and the larger scale, in which the building block is referred to as a ''depositional sequence.'' The definition of a depositional system thus parallels the definition of a dispersal system, and a depositional system can be viewed as the ''fossilized hard parts'' of a dispersal system.

Granulometric facies fall into three fundamental types (Fig. 2). In the proximal environments of a dispersal system, fluid power is high, leading to high levels of stratal condensation, and an *amalgamated sand facies* is deposited. The environment is sufficiently energetic that mud beds are never deposited, or are deposited only as the capping portions of sand–mud couplets and are destroyed by the subsequent event. The beds thus constitute a condensed section, in which condensation is a consequence of the energetic nature of the dispersal environment. While ''amalgamated'' technically means ''thoroughly mixed,'' the term has been used in stratigraphy to indicate that stratal contacts are sand-on-sand. Farther down the dispersal system there is less condensation, and an *interstratified sand and mud facies* is deposited. It has the greatest sand-bed count per unit thickness in the section (Aigner and Reineck 1982). Yet farther seaward, the section is again condensed, in this case because of the reduced sediment supply. A *lami-*

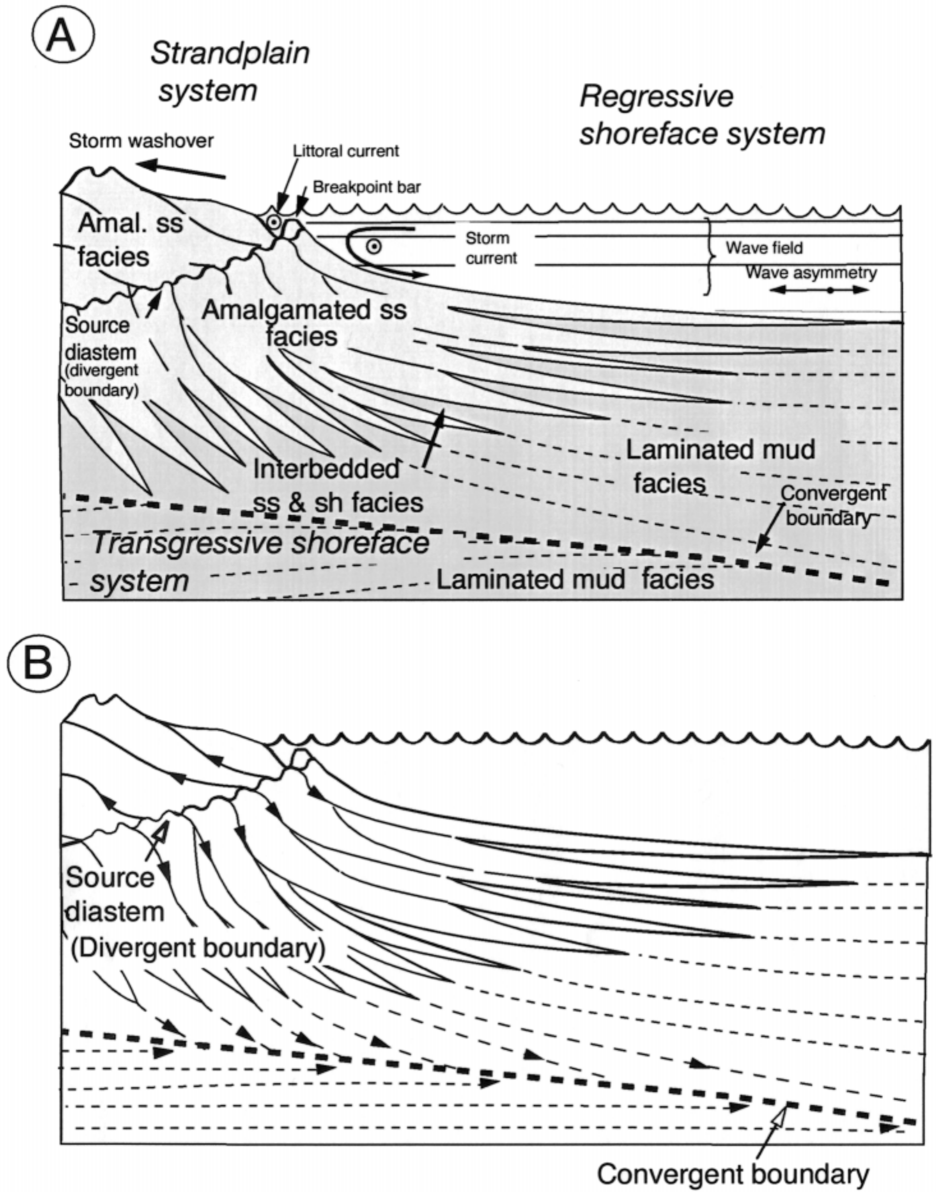

FIG. 3.—''Depositional Systems Template,'' configured for a regressive shoreface–shelf setting. **A)** Facies template configured for a regressive, rising-sea-level setting (supply exceeds accommodation). Dispersal environments omitted for clarity, but conventions are otherwise the same as in Figure 2. Outline letters describe depositional systems. **B)** Panel A modified to show grain trajectories, and their relationship to divergent and convergent boundaries.

nated or bioturbated mud facies is deposited. Finally, in the most seaward position, the rate at which sediment is supplied and the grain size determined by progressive sorting may both fall below critical levels, so that even the weaker wave power expended on this deeper bottom is adequate, or more than adequate, to bypass this reduced load. Deposition cannot occur, and the bottom may be winnowed or eroded. Such a surface can be considered the source environment of a new, ''downstream'' depositional system, leading, for instance, to deposition on a continental slope below a starved outer shelf. The double names applied to the facies described above contain a grain-size term describing the dominant grain size and a stratal term describing the vertical grain size variation. These names reflect both kinds of textural gradients present: gradients in progressive sorting, affecting mean grain size, and gradients in condensation, affecting stratal architecture.

EASTRERN SHORE STUDY AREA

Late Pleistocene Evolution of Virginia's Eastern Shore Peninsula

This section applies the conceptual model for granulometric facies to the Quaternary section of Virginia's ''Eastern Shore'' Peninsula, which is the southern extension of the Delmarva Peninsula (Delaware, Maryland, Virginia; Fig. 1). The Eastern Shore Peninsula is a Quaternary spit complex, with successive segments having formed during successive late Quaternary highstands of the sea (Mixon 1985; Foyle and Oertel 1992, 1997). The main spit segments are the Accomack Member of the Omar Formation (Accomack spit) and the Butlers Bluff Member of the Nassawadox Formation (Nassawadox spit, Fig. 1; Mixon 1985, their fig. 2). Toscano (1992) and Toscano and York (1992) dated the Accomack Member as oxygen isotope stage 7, deposited 200,000 yr BP. This date is substantiated by uranium-series dating of corals (Szabo 1985) and amino-acid racemization tests of mollusks (Wehmiller et al. 1988) from the Omar Formation. In Accomack County, Virginia, the correlative unit coarsens upward and contains medium-grained to coarse-grained sands and gravels as well as minor amounts of fine-grained sand and mud (Mixon 1985). Mixon (1985) suggested a nearshore to barrier-spit depositional environment.

The initial deposit of the Nassawadox Formation (Stumptown Member; Mixon 1985) is found only in the subsurface and constitutes a transgressive fluvial–estuarine fill within the Exmore Paleochannel, which was the channel of the Susquehanna River during the preceding lowstand (see cross

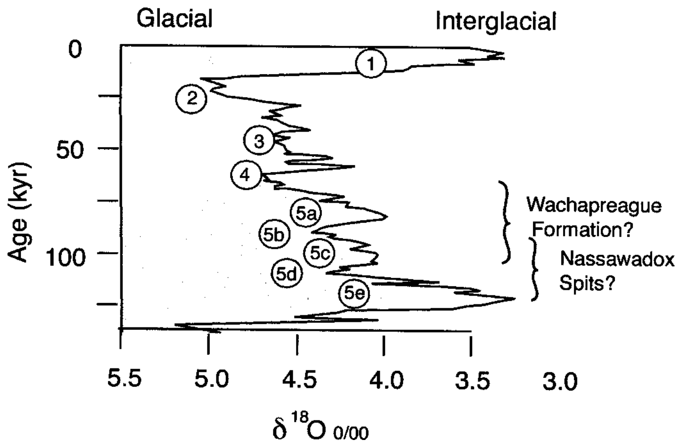

FIG. 4.—Oxygen isotope curve showing the relationship of the Wachapreague Formation (oxygen isotope stage 5c or 5a) to the Butlers Bluff Formation (Nassawadox spit; oxygen isotope stage 5e). The $\delta^{18}O$ curve from the foraminifera *Uvigerina senticosa* per mil to Pee Dee Belemnite in North Atlantic core V19-30. Data from Shackelton and Pisias (1985).

section, Fig. 1). It was deposited around 127,000 yr BP, during oxygen isotope stage 5e (Fig. 4; Mixon 1985; Szabo 1985; Toscano 1992; Toscano and York 1992). At the culmination of the transgression, the Butlers Bluff Member prograded southward across the filled paleochannel as a barrier spit, paused as sea level fell again, and a further channel was incised (Belle Haven Paleochannel; Foyle 1994). The unit then resumed its southward progradation to form a second segment of the Nassawadox spit (Fig. 5B). The Butlers Bluff Member is a clean, well-sorted, medium-grained to coarse-grained, cross-stratified sand, similar to facies E and G of the Accomack Member of the Omar Formation (Mixon 1985).

On the southern end of the Eastern Shore Peninsula, the Butlers Bluff Member of the Nassawadox Formation is disconformably overlain by the somewhat finer, horizontally stratified sands of the Wachapreague Formation (Mixon 1985), which are tentatively assigned to isotope stage 5a (Foyle 1994; See cross section, Fig. 1). The narrow outcrop belt of the Nassawadox Formation forms an ''upland surface'' on which recurved, southward-facing beach ridges are visible, whereas the lower surface of the Wachapreague Formation is molded into the Bell Neck Strand Plain (Mixon 1985), whose north–south trending beach ridges prograded nearly due east (Fig. 1).

Formation of the Holocene Barrier–Lagoon System

Holocene transgressive lagoon and barrier-island deposits onlap the western flank of the Pleistocene succession of the Eastern Shore Peninsula (Mixon 1985), and their mainland-fringing marshes are burying the beach

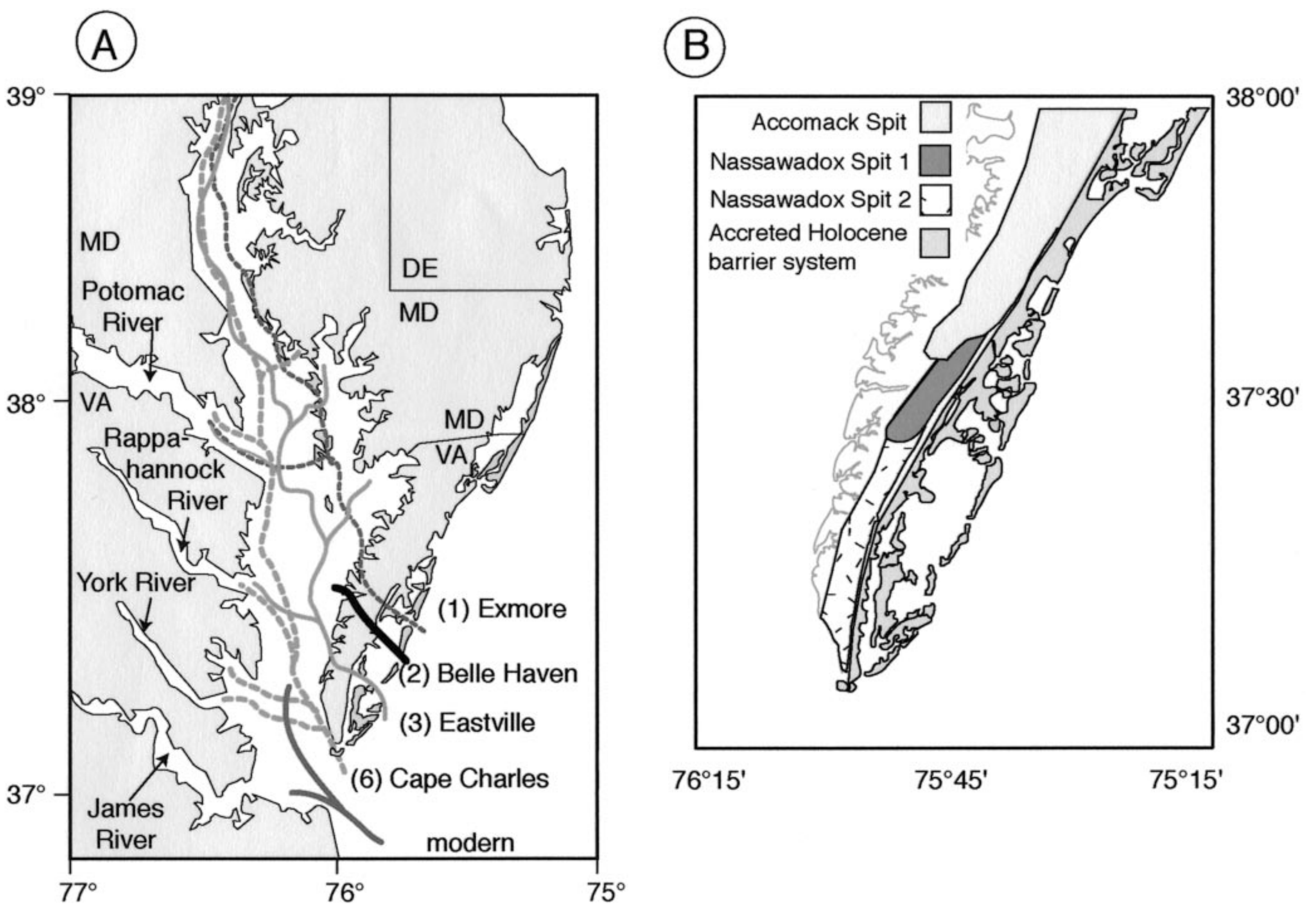

FIG. 5.—**A)** Traces of successive lowstand Susquehanna River paleochannels. The Exmore, Belle Haven, Eastville, and Cape Charles paleochannels (named from right to left) extend beneath Virginia's Eastern Shore Peninsula. They are of successively younger age. **B)** Successive highstand spit segments on the Eastern Shore Peninsula. Modified from Colman et al. (1990).

ridges of the Bell Neck Strand Plain (Fig. 1). These deposits are a response to the late Holocene rise in sea level, which includes both a eustatic component (1.0–1.5 μm/yr; Fairbanks 1989; Donoghue 1990) and subsidence component (1.2 μm/yr; Holdahl and Morrison 1974; Hicks and Hickman 1988; Peltier 1990). The barriers appeared in approximately their present position less than 6,000 yr BP (Newman and Rusnak 1965). Fisher (1968) interpreted the coastal compartments of the Middle Atlantic Bight (straight segments between estuary mouths) as responses to the dominant northeast approach of storm waves. He described a repeating pattern of eroding mainland beach (northern end), followed by barriers with open-water lagoons, followed in turn by barriers with marsh-filled lagoons. The Eastern Shore barriers belong to the latter class. They are characterized by deep inlets (40–60 m) separating short, narrow barrier segments (2–10 km long) with high retreat rates (1–3 m/yr; Rice and Leatherman 1983; Shideler et al. 1984; Demerest and Kraft 1987; Finkelstein 1988, 1992; Oertel et al. 1992).

Oertel et al. (1992) have argued that this pattern is the consequence of the encroachment of the barrier–lagoon system on the Mappsburg Scarp (127,000 yr BP shoreline; Fig. 1). In this model, the steeper slope at the toe of the scarp has resulted in a narrower and shallower lagoonal system. The lagoon's reduced volume is easily filled to near high-tide level by muds eroded from the adjacent sea floor (Newman and Munsart 1968; Finkelstein and Ferland 1987; Finkelstein and Kearney 1988; Finkelstein 1992). As a result, tidal creek systems form. Instead of a radial intake of ebb tidal discharge from the open lagoon, inlets experience the ebb tide as a jet-like discharge collimated by the banks of a creek, which deeply incises the tidal inlets.

Chesapeake Bay Mouth Shoal Deposits

Episodic, along-coast progradation of the Eastern Shore spit complex through the late Quaternary has reduced the width of Chesapeake Bay mouth to 31 km. Although the region is microtidal, the tidal prism of Chesapeake Bay is sufficiently large to generate tidal currents in the restricted mouth that locally exceed 300 cm s^{-1}. As a consequence, much of the sand transported by littoral processes to Fisherman Island (at the end of the Peninsula) does not remain there but is bypassed to a deeper system of tidal transport and carried from there into the mouth of Chesapeake Bay. This sand nourishes a ''zigzag submarine spit,'' deflected by channels dominated alternately by ebb tidal discharge and flood tidal discharge, which interfinger across the shoal crest (Ludwick 1970a, 1974; Hobbs et al. 1986; Colman et al. 1988; Colman et al. 1990; Colman et al. 1992).

HOLOCENE DISPERSAL SYSTEMS ON THE EASTERN SHORE PENINSULA

General

The conceptual model for granulometric facies requires that a facies assemblage (depositional system) be understood in terms of the lateral succession of dispersal environments (dispersal system) that created it. The late Holocene transgressive dispersal system described above is not fully analogous to the highstand system of isotope stage 5e, but important parallels exist, which can be used to test the granulometric facies model. A fully quantitative resolution of sediment discharge across the inner Virginia shelf and shoreface is beyond the scope of this study. Nevertheless, published studies of sediment dynamics over the last twenty years have greatly enriched our understanding of sediment dispersal in shallow marine settings. Studies that have taken place on the Virginia coast and inner shelf, plus related studies elsewhere, allow us to develop generalized maps of the Eastern Shore dispersal system by means of sets of rules for each dispersal subsystem. In this section, a series of such portrayals are developed. They are used to interpret the analogous Pleistocene depositional systems in the following section.

Transgressive Shoreface System, Smith Island

Upwards of 10^6 m^3 of sand is transported southward along the surf zone of the Southern Delmarva coast each year, bypassing the inlets on the curved crests of the ebb tidal deltas (Byrne et al. 1974; Boon 1975; Byrne et al. 1975; DeAlteris and Byrne 1975; Rice 1977; Slingerland 1977; Boon and Byrne 1981). Below the surf zone, the transgressive shorefaces of Delmarva barriers are migrating landward at rates of a meter a year or more (Moody 1964; Newman and Rusnak 1965). Rates of retreat are not constant. Successive years of moderately intense storms serve to aggrade the shoreface at the expense of the surf zone, until a major event, such as the Ash Wednesday Storm of 1962 (Moody 1964) or the Halloween storm of 1991 (Wright et al. 1994), strips the accretion of several decades. Part of this sand is deposited as washover fans on the lagoonal sides of the barriers (Leatherman et al. 1977), but more is swept off the shoreface and onto the inner shelf floor by downwelling storm currents (Moody 1964; Wright et al. 1986). Because of the frequency of ''scale-matching'' northeaster storms, inner-shelf transport is also generally to the south. In these events, a northeaster storm, whose diameter approximates the length of the bight, crosses the bight, so that for a period of time the isobars of atmospheric pressure parallel the isobaths of the shelf floor, eliciting a coherent geostrophic southward flow (summary of references in Swift et al. 1986). A system of shoreface-connected sand ridges from the middle shoreface of southern Smith Island trends obliquely north, towards the inner-shelf floor. Shoreface-connected sand ridges in the Middle Atlantic Bight form as responses to peak storm flow (Swift et al. 1986). Sediment flux is typically southward and offshore, obliquely across both the sand-ridge crests and their intervening troughs. This information can be combined with studies undertaken elsewhere to generate the following rules for bedload sediment dispersal on the Virginia Coast.

- At time scales of fifty years or greater, the entire shoreface in transgressive sectors of the Middle Atlantic Bight is undergoing erosional retreat (e.g., Moody 1964).
- Net sediment flux in the surf zone of the Middle Atlantic Bight (0 to 3 m water depth) is southward and parallels isobaths (Fisher 1968; Wright et al. 1987). Averaged over time intervals sufficient to include major storm events (3–10 yr) there is an onshore component of transport, reflecting episodic storm washover of the barrier (Leatherman et al. 1977)
- Grain size on the beaches of coastal compartments of the Middle Atlantic Bight fines to the south (Swift 1975).
- Sediment transport on the middle and lower shoreface is directed southward and offshore, and is oblique to isobaths (Ludwick 1978; Swift et al. 1985; Wright et al. 1986).
- Sediment transport over storm-generated sand ridges in the Middle Atlantic Bight is typically south and offshore, obliquely across the crests (Palmer et al. 1975; Figueiredo et al. 1981).
- The intensity of this flux diminishes seaward as a function of increasing water depth and decreasing intensity of wave orbital motion during peak storm flows (Swift et al. 1985; Héquette and Hill 1995).
- Sand on the inner Delmarva shelf (approximately the 20 m isobath) fines alongshore to the southwest, down the transport path, from 1.8 ϕ at Chincoteague shoals to 2.4 ϕ at Smith Island (Nichols 1972).
- The troughs between the ridges and the shoreface undergo erosion, as do the up-current flanks of the ridges, while the crests and down-current flanks aggrade (Swift and Field 1981).

The preceding patterns of behavior can be applied to a central sector of the Smith Island shoreface to provide the qualitative estimate of the bedload dispersal system presented in Figure 6. The arrows in Figure 6 are not vectors, because absolute values for mean annual sediment transport rates are not known. However, arrow lengths qualitatively indicate zones of transport acceleration and divergence required by the behavior outlined

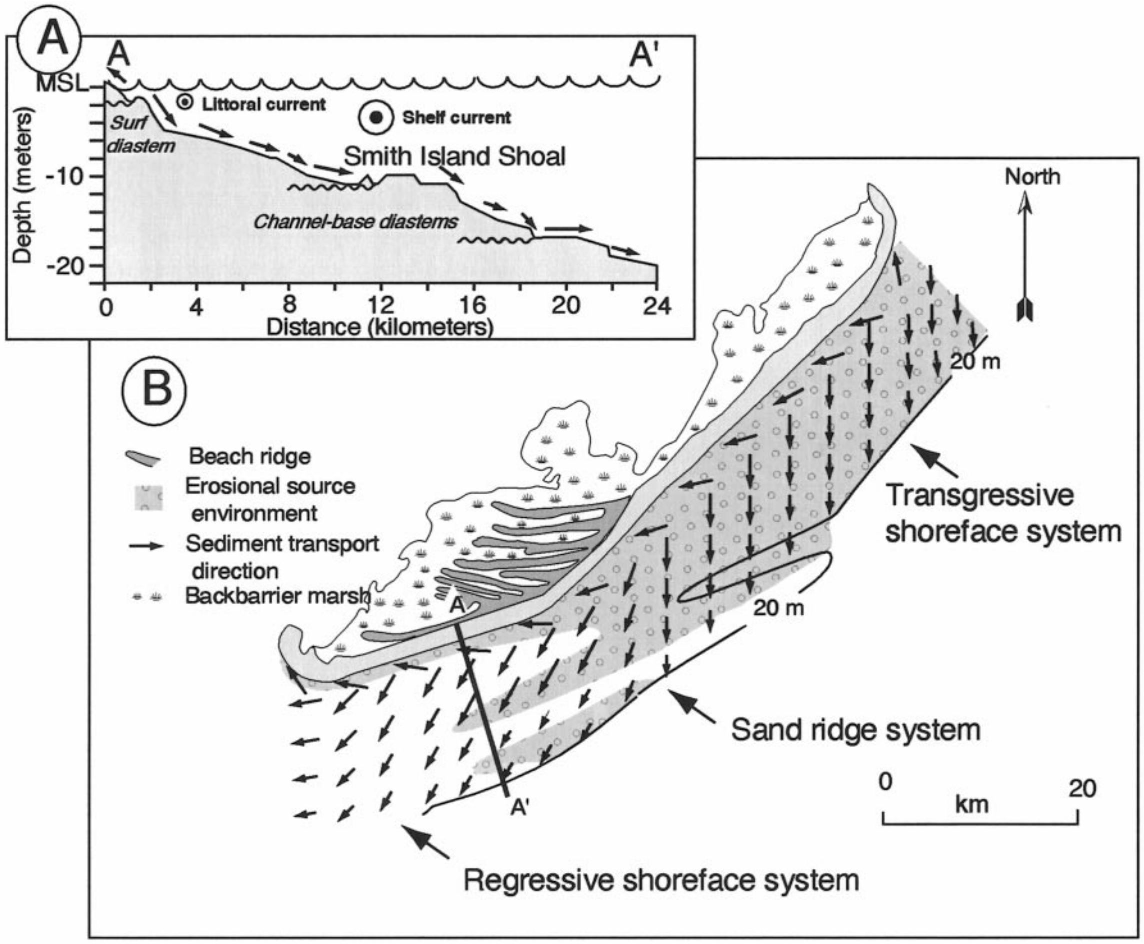

FIG. 6.—Transgressive and regressive shoreface dispersal systems, Smith Island. The arrows are not vectors: absolute values for mean annual sediment transport rates are not known. Arrow lengths qualitatively indicate zones of transport acceleration and divergence required to explain regional flow observations. In the cross section, arrows provide a qualitative estimate of bedload sediment transport in the plane of the section. Eroding source environments are designated in the map view, and the equivalent source diastems are figured in the cross section. See text for explanation of rules on which this interpretation is based, and Figure 10 for location.

above. Source environments are designated, and the equivalent source diastems are figured in the cross section. In the cross section, a transport divergence is seen in the surf zone, equivalent to the divergence seen in plan view. In the cross section, a surf diastem is shown as forming at this divergence. Farther down on the lower shore face of the cross section, two of the Smith Island ridges appear. There is flow divergence in each of the troughs, since flow in the trough is much more nearly contour parallel than on the crest, and erosion occurs on the landward flank of each ridge (not resolved on the plan-view map). A channel-base diastem consequently is initiated in each trough.

Regressive Shoreface System, Smith Island

The southern end of Smith Island is oriented more nearly east–west than is the central section and is prograding rapidly to the south as a recurved spit, generating a subaerial strand plain as it does so (Fig. 6). As a consequence of the rotation of the shoreline, the mean annual wave power experienced by the beach berm of this sector decreases rapidly to the south (Goldsmith 1974), resulting in a net surplus of sand in the littoral drift system. We therefore propose a modified description of the dispersal system in this sector, to include the following additional generalizations.

- At time scales of 50 years or greater, shorefaces in the Middle Atlantic Bight that face southward are undergoing southward progradation (Leatherman et al. 1977; Swift et al. 1972).
- In the Middle Atlantic Bight, scour and fill of the sea floor in response to coastal storms attains a maximum in the surf zone, between the berm and the 3 m isobath (Goldsmith et al. 1974; Wright et al. 1987).
- As successive bars migrate onshore and weld to the beach in these areas, the surf zone is displaced seaward (Wright et al. 1987, 1988; Greenwood et al. 1984).

The preceding behavior patterns may be applied to the southern sector of the Smith Island shoreface to provide the qualitative estimate of the bedload dispersal system (Fig. 6B). Source environments are designated, and the equivalent source diastems are figured in the inset. In the latter, arrows based on the same rules provide a qualitative estimate of bedload sediment transport in the plane of the section (Fig. 6A). The surf-base scour is a source environment. It is buried as a disconformable surface (source surf diastem) as indicated in the cross section (Fig. 6A).

Marginal Shoal System, Fisherman Island

Along the south flank of Fisherman Island, the shoreface loses its simple exponential profile, as Fisherman Shoal (the most onshore of the baymouth tidal shoals) zig-zags from the floor of the channel mouth up to the upper

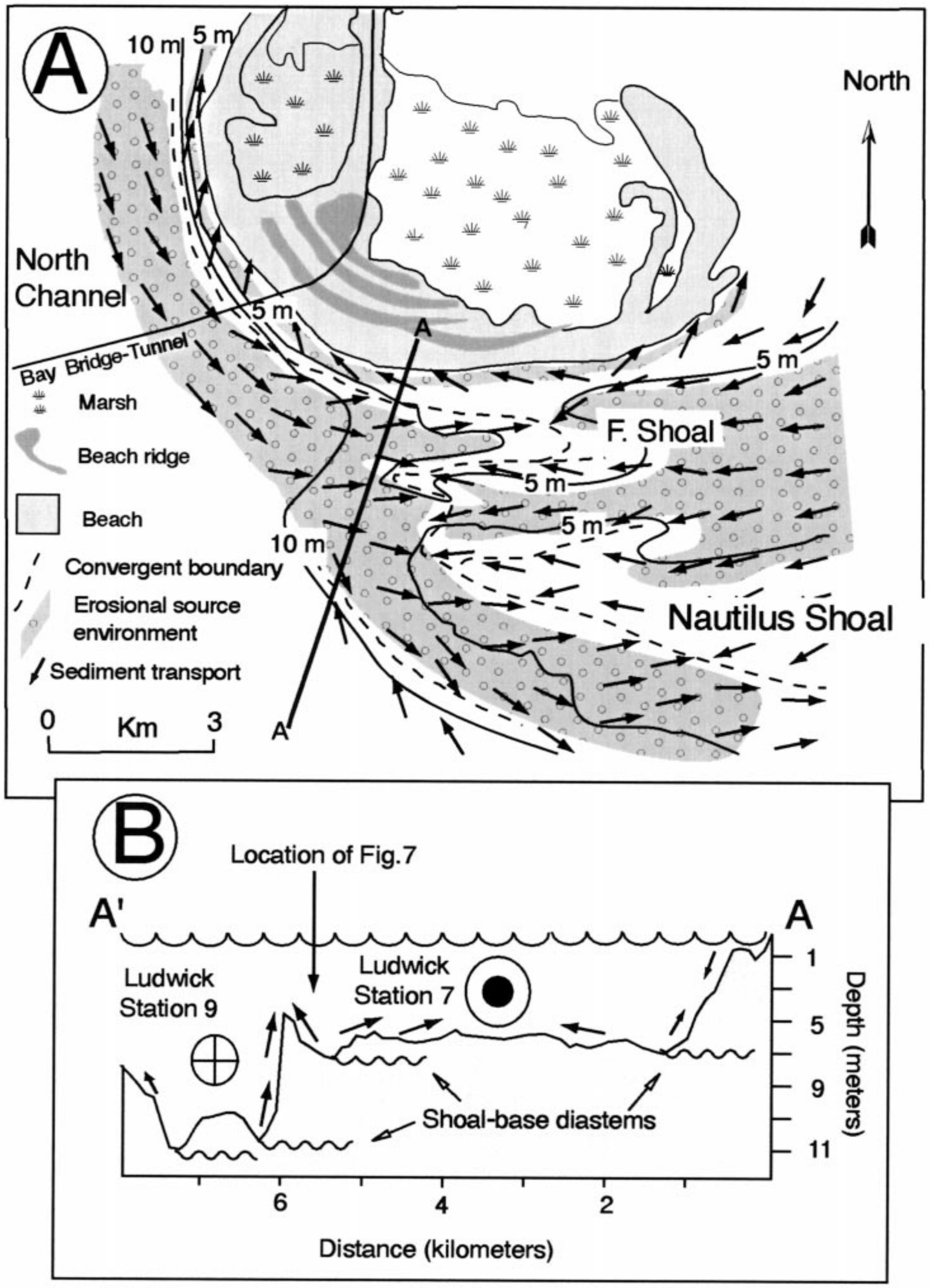

FIG. 7.—Regressive shoreface and marginal shoal dispersal systems, Fisherman Island. The arrows are not vectors: absolute values for mean annual sediment transport rates are not known. Arrow lengths qualitatively indicate zones of transport acceleration and divergence required to explain regional flow observations. In the cross section, arrows provide a qualitative estimate of bedload sediment transport in the plane of the section. Eroding source environments are designated in the map view, and the equivalent source diastems are figured in the cross section. See text for explanation of rules on which this interpretation is based, and Figure 10 for location.

shoreface (Fig. 7A). The baymouth shoals can be viewed as partitions separating tidal channels, which are typically ''blind'' or ''dead end'' channels that terminate in either the ebb or flood direction. The first case is referred to by Ludwick (1970) as an ''ebb sulcus'' and the former case as a ''flood sulcus.'' The channels are correspondingly ebb- or flood-dominated, in that over the duration of a tidal cycle, the ebb or flood discharge at a station in the channel is greater than the alternate discharge. The convergence of two tidal shoals towards the blind end of a tidal sulcus leads to the formation of a ''parabolic'' tidal shoal, or in some cases a double parabola or ''Z'' shoal.

The pattern of sediment transport in the shoal complex of the Chesapeake Bay mouth has been computed by Ludwick (1975; see also Ludwick 1970, 1972, 1974), and can be summarized as follows:

- The passage of the tidal wave from the shelf into the shallow bay mouth creates a strong horizontal gradient in tidal phase (Ludwick 1970, 1974).
- The cohesionless substrate is unstable in the presence of the gradient and a tidal channel–tidal shoal system evolves (Ludwick 1975).
- Bottom sediment flux is most intense along the channel axes where the water is deepest and experiences the least frictional retardation. Bottom sediment transport is least intense along shoal crests (Ludwick 1975).
- Sediment flux diverges along eroding channel axes and converges along aggrading shoal crests (Wells and Ludwick 1974; Ludwick 1975).
- Shoals aggrade upward into the zone of wave orbital motion until tidal aggradation during the quiescent summer periods is balanced by crestal degradation by winter storm waves (Granat and Ludwick 1980; Ludwick 1967, 1974).

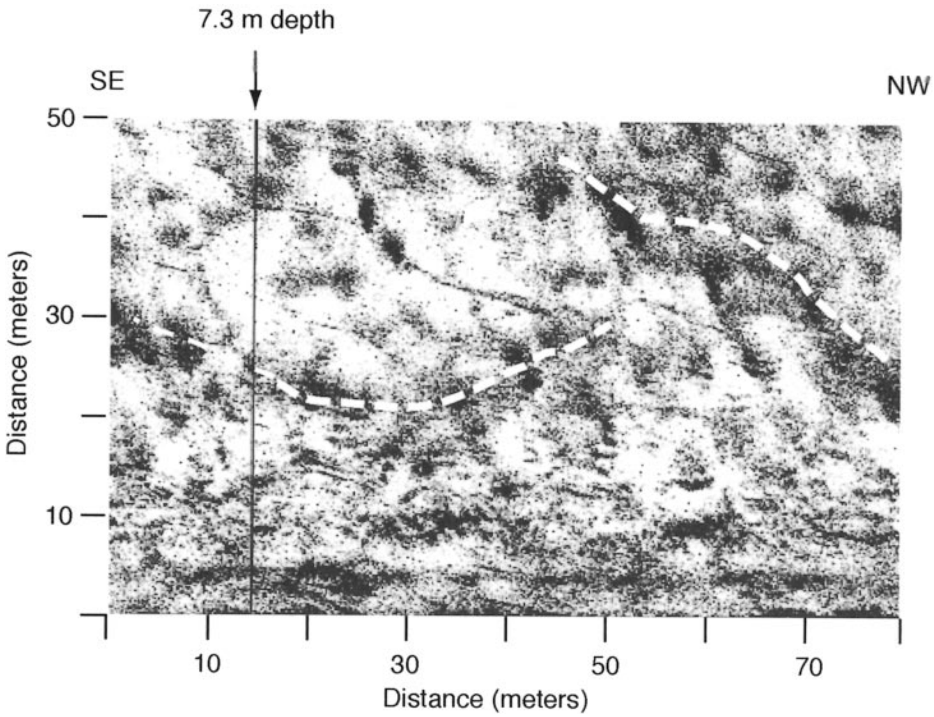

FIG. 8.—Interpreted sonogram from Nautilus Shoal in the mouth of Chesapeake Bay from November 1997. Dashed white lines trace the crests of sinuous sand waves. Highly sinuous megaripples and relatively straight wave-dominated small-scale ripples are also apparent. Location of sonogram is shown in cross section of Figure 7. Sonogram is from port transducer only.

- Because the opposite sides of partition shoals tend to have an opposing sense of transport, the shoal tends to serve as a sand circulation cell, or closed loop in the sediment dispersal pathway (Ludwick 1974).
- Fluid discharge and sediment dispersal patterns tend to be skewed relative to the shoal morphology in that one side of the ridge or the other experiences a more intense sediment flux, so that the ridge as a whole tends to migrate laterally through time (Ludwick 1975).

This general behavior leads to the qualitative analysis of sediment dispersal on the southern margin of Fisherman Island (Fig. 7A). Side-scan sonar profiles across Nautilus Shoal indicate that the sand of the shoal is transported by migrating flow-transverse bedforms at several spatial scales (ripples, megaripples, sand waves; see Fig. 8 and also Ludwick 1970, 1972). During the southward progradation of the marginal shoal complex across the mouth of Chesapeake Bay, scours associated with the channels between the sand shoals are buried as disconformable surfaces (channel-base diastems), and they are so shown in the cross section (Fig. 7B).

Baymouth Shoal System, Nine Foot Shoal

Nine Foot Shoal and Inner Middle Ground Shoal in Chesapeake Bay Mouth together constitute a ''Z-shaped'' shoal south of North Channel. Conclusions for tidal bedload as presented above lead to the qualitative analysis of sediment dispersal on the Z-shaped shoal (Fig. 9). During the southward progradation of the marginal shoal complex across the mouth of Chesapeake Bay, scours associated with the channels between the sand shoals are being buried as disconformable surfaces, and they are so shown in the cross section (Fig. 9B).

Figure 10 illustrates the integrated shallow-marine bedload dispersal system, for modern, near-highstand conditions on the north side of Chesapeake Bay. At the scale of this diagram, tidal shoals cannot be resolved as individual sand circulation cells, and transport appears to be continuous along the zigzag crest of the shoal complex.

DEPOSITIONAL SYSTEMS OF THE LATE PLEISTOCENE HIGHSTAND

General

The stratigraphic succession of isotope stage 5 (successive members of the Nassawadox Formation, Fig. 1) was deposited under near highstand conditions to fully highstand conditions, at approximately 127,000 yr B.P. The upper part of this succession is exposed in the Oyster borrow pit north of the town of Oyster, Virginia, and at the Chesapeake Bay shoreline at Butlers Bluff (Kiptopeke State Park, Cape Charles, Virginia). See Mixon (1985) for details of these localities. This section reviews facies associations at these localities and interprets them in the light of the analogous Holocene depositional systems.

On the basis of criteria established for granulometric facies (Swift et al. 2003), a single facies, the amalgamated sand facies, is present in the Nassawadox Formation. However, well-defined subfacies can be discerned, on the basis of primary structures, mean grain size, and percent lithic gravel (Table 1). A horizontally stratified sand subfacies is horizontally stratified, and consists of fine- and very fine-grained sand (mean particle diameter less than 2.00 ϕ or 250 μm). Such sand characteristically travels in short-term suspension, and the deposits of such suspension events are horizontally stratified, upward-fining beds.

The cross-stratified sand subfacies exhibits high-angle cross-stratification and consists of sand coarser than 2.00 ϕ (250 μm, see Table 1). Such sand travels as bedload, primarily via bedform migration (Dyer 1984), hence the association with cross-stratification. A cross-stratified, shelly, gravelly sand subfacies is defined by the presence of 5 to 50% gravel and *Spisula solidissima* casts. This subfacies is intimately associated with the cross-stratified sand subfacies, and was deposited as a basal lag by migrating megaripples. The grain-size relationships of these subfacies are presented in Figure 11, and their stratigraphic relationships, as revealed in the face of the Oyster Borrow pit, are illustrated in Figure 12. Their character, and the rationale for their classification, are discussed in greater detail in Muller et al. (1999). In the rest of this paper, these subfacies are simply referred to as facies.

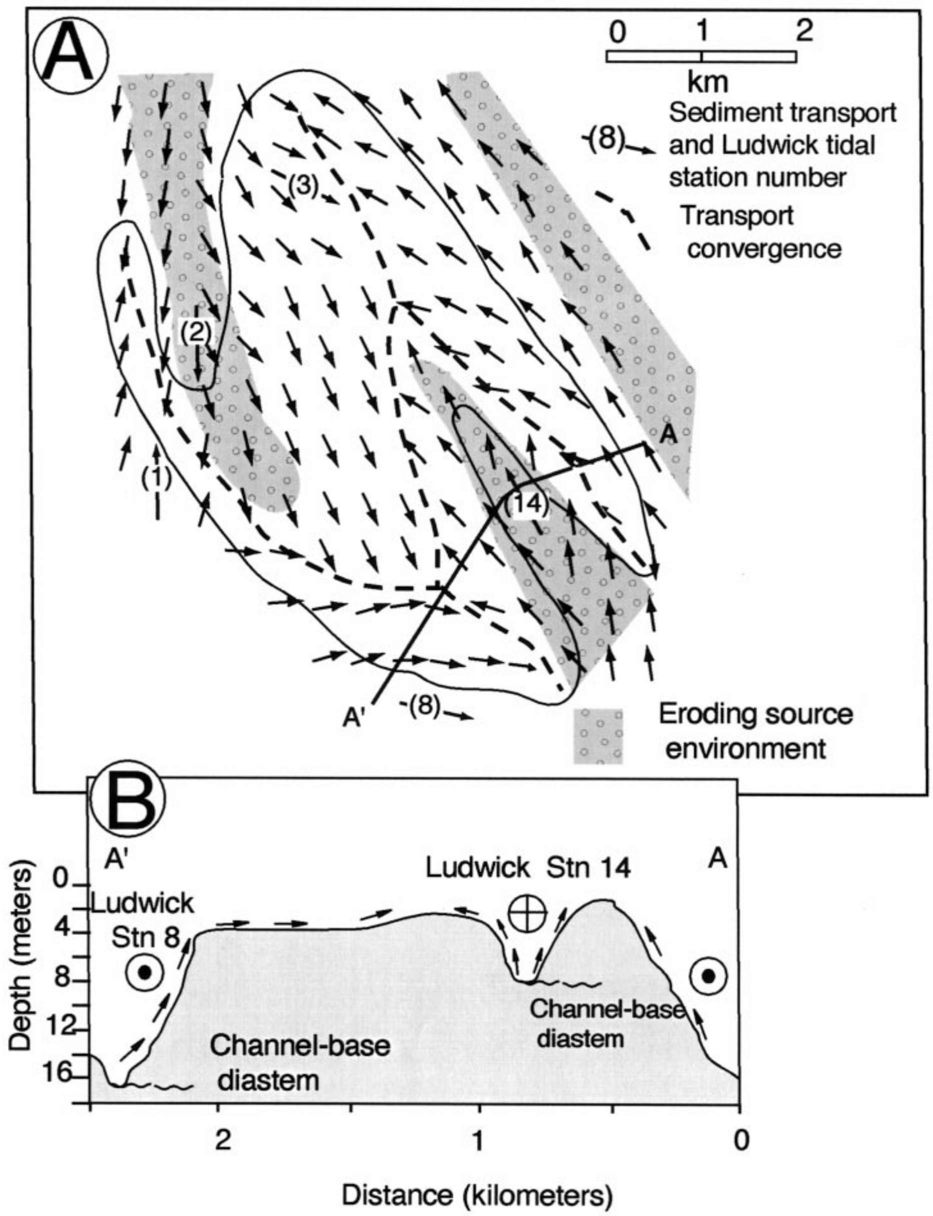

FIG. 9.—Baymouth shoal dispersal system, Chesapeake Bay mouth. The arrows are not vectors: absolute values for mean annual sediment transport rates are not known. Arrow lengths qualitatively indicate zones of transport acceleration and divergence required to explain regional flow observations. In the cross section, arrows provide a qualitative estimate of bedload sediment transport in the plane of the section. Eroding source environments are designated in the map view, and the equivalent source diastems are figured in the cross section. See text for explanation of generalizations on which this interpretation is based, and Figure 10 for location.

The three facies of the Nassawadox Formation occur in distinctive facies assemblages (depositional systems) whose spatial relationships are revealed by ground-penetrating radar (GPR) profiles (Fig. 13). In the GPR profiles, the bounding surfaces of the facies associations are well-defined reflectors. Two other classes of less well-defined reflectors are also seen in Figure 13. First-order reflectors are the most continuous, with continuities in excess of 500 m. Second-order reflectors are less continuous (10–40 m). Third-order reflectors cannot be traced farther than 10 m. When GPR profiles are traced into borrow pits or along exposures where the stratigraphy is exposed, the first-order reflectors appear as bounding surfaces of depositional systems, in that genetically related facies occur between two bounding surfaces but do not cross either surface, in accord with the definition of a depositional system formulated by Fisher and McGowen (1967). While we have found the facies interpretations offered by Mixon (1985) to be very useful, the facies that we delineate within the highstand Butlers Bluff Member are not directly comparable to the facies described by Mixon (1985) in the Butlers Bluff and Stumptown members of the Nassawadox or in the Accomack Member of the Omar Formation. Rather, each Mixon ''facies'' appears to be the equivalent of a depositional system as the term is used in this paper. The following depositional systems can be identified in Figure 12.

Baymouth Shoal Depositional System

This depositional system consists of the cross-stratified sand facies intercalated with the shelly gravelly sand facies, over vertical scales of 10–60 cm (compare Figs. 12 and 14). Trough cross-sets are typically large near the base of the section (up to 14 m wide) and become smaller (to 30 cm wide) and finer-grained up section. Thick gravel lenses occur at the base of basal cross-strata sets, with thinner basal gravel lenses up section, with gravel-size material consisting largely of disarticulated valves of the common Atlantic surf clam, *Spisula solidissima.* Tidal shoals in the mouth of modern Chesapeake Bay are blanketed by fields of sand waves of this scale (Fig. 8), and similar sands and shelly gravelly sands have been de-

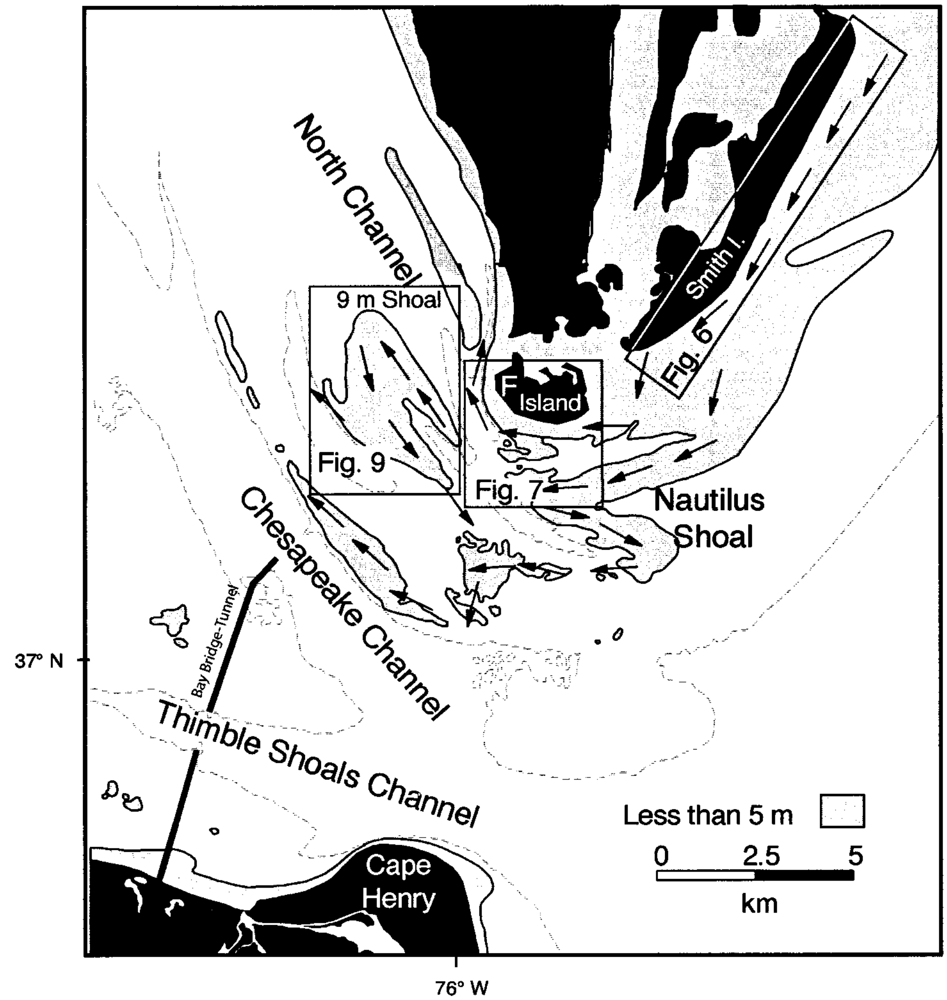

FIG. 10.—Map of Chesapeake Bay mouth, showing locations of Figures 6, 7, and 9. Generalized sediment transport is also indicated. Compare with Figure 1.

scribed from them (Ludwick and Wells 1974; Wells and Ludwick 1975; shaded field, Fig. 11). We infer, therefore, that the cross-stratified successions of Figure 12 were deposited by baymouth shoal dispersal systems of the kind described earlier in this paper. These facies successions would fit the definition for a depositional system presented above if the gravel-rich basal sections are envisioned as a proximal facies complex and the gravel-poor upper sections as a distal facies complex. In this scheme, the lower bounding surfaces (OR-5, OR-6 in Fig. 12) are channel-base diastems cut by lateral channel migration, and they serve as the source diastems for the upward-fining facies successions that migrate over them. These diastems have up to 2 m of relief over a horizontal extent of 20 m and locally truncate underlying strata.

Shoreface Depositional System

Two of the bed successions above the Baymouth Shoal deposits consist primarily of the horizontally-stratified sand facies (Fig. 12). They are separated by an interval of cross-stratified sand and shelly gravelly sand similar to the underlying shoal deposits. The two intervals of horizontal stratification can be treated as a single upward-coarsening section (long arrow, Fig. 12B). Trace fossils of the *Skolithos* and *Cruziana* ichnofacies (Bromley 1996) are present in each. The sands are fine-grained to very fine-grained and resemble those found on the progradational sector of the modern shoreface of the lower Eastern Shore Peninsula (Nichols 1972; lightly shaded pattern, Fig. 11). We infer that these successions were deposited by a prograding shoreface dispersal system. The shoreface dispersal system was apparently not continuous but was interrupted by a marginal shoal dispersal system (compare with Fisherman shoal, Fig. 7). In Figure 12, the lower shoreface interval rests conformably on the Upper Baymouth Shoal deposit (Reflector OR-4; convergent boundary; see definition above) and is capped by a divergent channel-base diastem (Reflector OR 3).

While the lower shoreface interval is relatively homogeneous, there are two thin, coarse, shelly laminae. These are interpreted as having formed during periods of significant erosion of the lower-shoreface dispersal environment, followed by resumed progradation of the spit (''multiple lower-shoreface systems'' Fig. 12). Their significance is considered below. The upper-shoreface interval rests conformably on the marginal shoal deposit (OR-2; another convergent boundary; Figs. 12, 14, 15). The upper bounding surface (OR-1) is a divergent boundary: a source diastem, and more specifically the surf diastem, whose formation has generated the facies succession that it caps. The lower bounding surface (OR-4) is a convergent system boundary.

TABLE 1.—*Classification scheme of facies in the Butlers Bluff Member (after Muller et al. 1999).*

Percent Gravel	Mean Diameter	Name
5–50% gravel	$>2.00\ \phi$	Cross-stratified, shelly, gravelly sand facies
$<5\%$ gravel	$>2.00\ \phi$	Cross-stratified sand facies
$<5\%$ gravel	$<2.00\ \phi$	Horizontally stratified sand facies

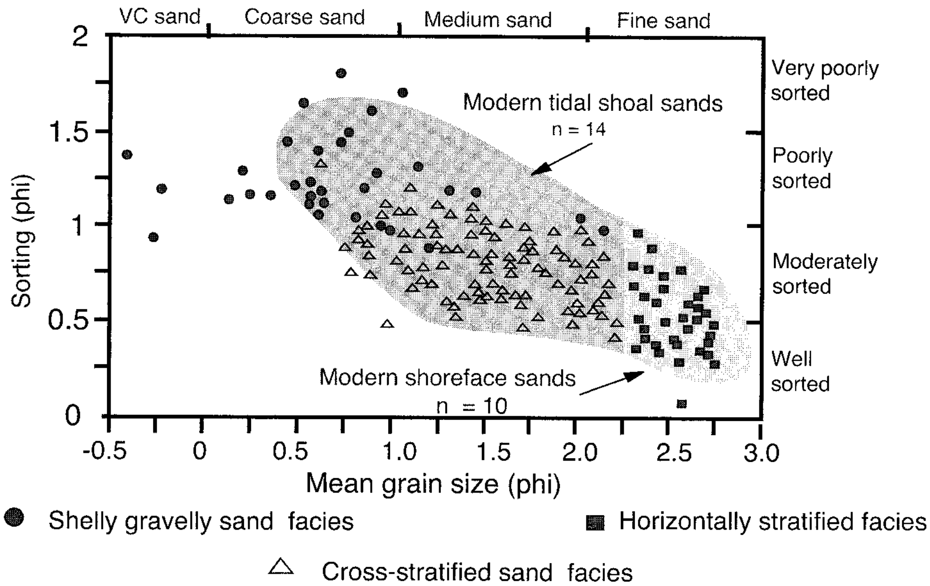

FIG. 11.—Comparison of grain-size characteristics for samples from the Butlers Bluff Formation with those of samples from analogous depositional environments of the modern Eastern Shore shoreface, and Chesapeake Bay mouth. Modern shoreface data is taken from Nichols (1972), and modern tidal shoal data is taken from Ludwick and Wells (1974).

Marginal Shoal System

This depositional system, like the baymouth shoal system, consists of the cross-stratified sand facies intercalated with the shelly gravelly sand facies. These deposits, sandwiched between the two shoreface intervals, closely resemble those of the baymouth shoal systems. The system is 3 m thick. Some cross-strata sets at the base exceed 60 cm in thickness and are over 8 m wide normal to the transport direction. The scale of cross-stratification significantly exceeds that observed in upper-shoreface deposits (e.g., Greenwood and Sherman 1984). Because the deposit is intercalated in a shoreface succession, it is best explained as a marginal shoal deposit similar to Fisherman Shoal on the south end of Fisherman Island, on the modern coast of the Eastern Shore (Fig. 7). The marginal shoal system rests on the channel-base diastem (OR-3; Figs. 12, 14, 15) that provided its sediment.

Strand-Plain Depositional System

This depositional system forms the upland surface of the Eastern Shore Peninsula (Fig. 1). The Peninsula is thought to have been subject to the

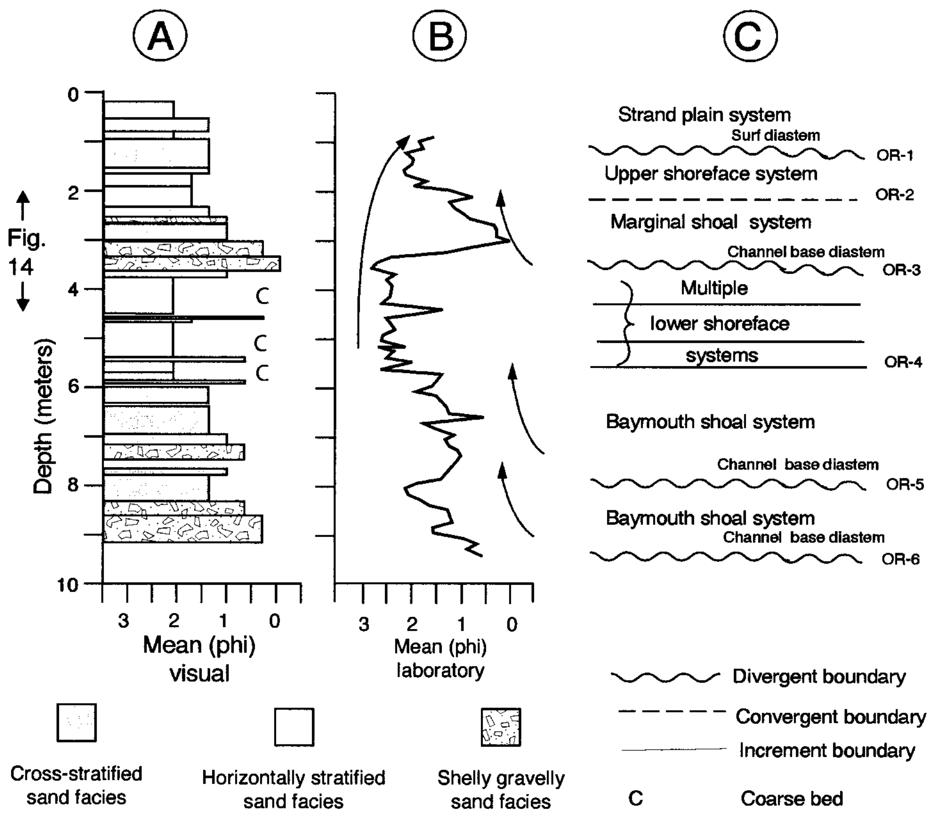

FIG. 12.—**A)** Log of measured section of core adjacent to the Oyster borrow pit, with facies designations based on visual estimation of grain-size. **B)** Grain-size profile indicating upward-coarsening trends, based on grain-size analysis by particle analyzer ($< 2\ \phi$) and sieving ($> 2\ \phi$). **C)** Interpretation of depositional systems and bounding surfaces. OR-1 through OR-6 are reflectors (R) detected near the Oyster pit (0) by ground-penetrating radar.

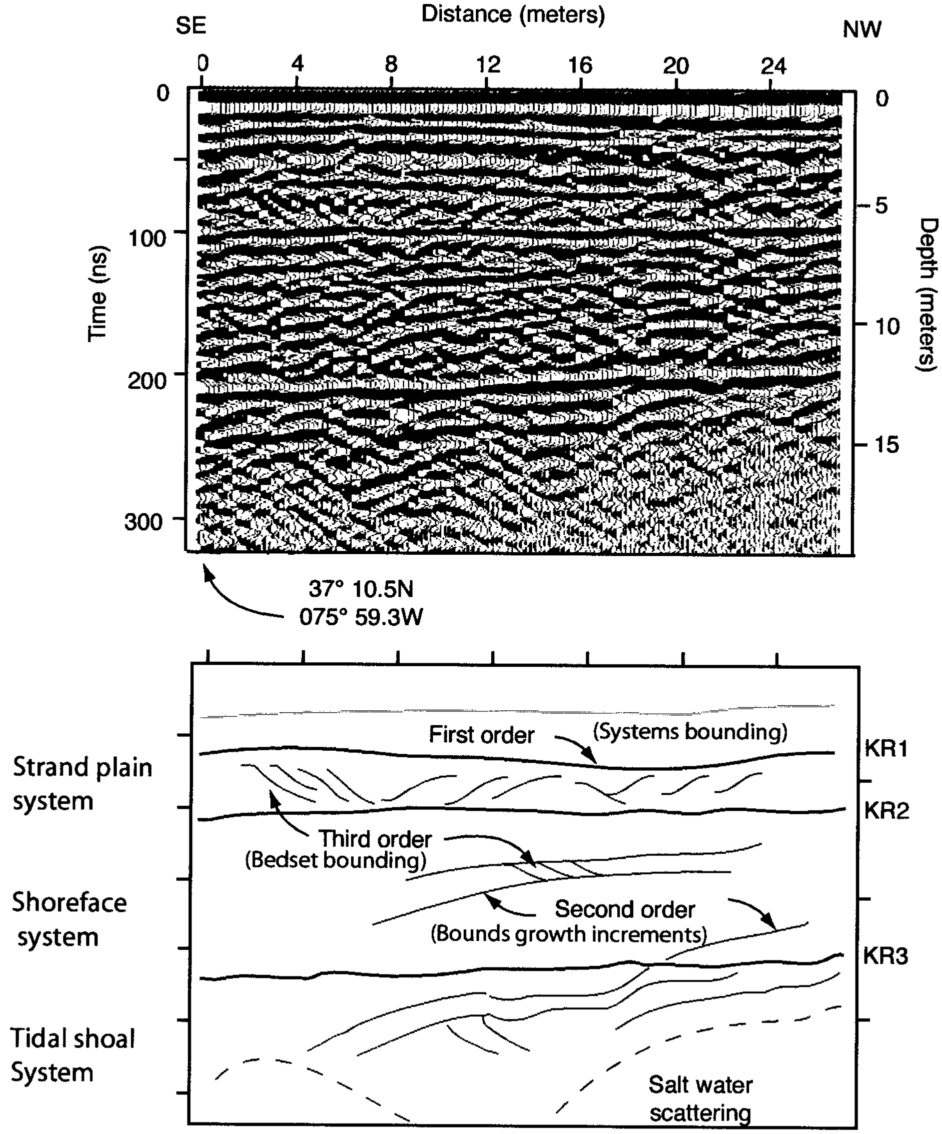

FIG. 13.—Ground-penetrating radar profile of the Butlers Bluff Member at the type locality (Kiptopeke Beach). First-order bounding surfaces are more continuous than second-order or third-order bounding surfaces. They are boundaries between facies assemblages (depositional systems). KR1 through KR3 are reflectors (R) detected at the Kiptopeke site (K) by ground-penetrating radar.

deposition of loess blown off the emerged floor of Chesapeake Bay during the 18,000 yr BP lowstand (Mixon 1985). As a consequence of subsequent soil-forming processes, a thick zone of iron enrichment largely obscures the properties of this system. However, aerial photography and topographic maps indicate that its upper surface is molded into recurved beach ridges (Figs. 1, 16), hence we infer that it is a strand-plain depositional system, similar to that seen at the southern end of Smith Island (Fig. 6). The strand-plain depositional system rests on the surf diastem (OR-1, Fig. 12) that provided its sediment.

Spit Growth Increments

At horizontal scales of 100 m to 1 km, an additional pattern of spatial organization appears. The growth of the ancestral Accomack and Nassawadox spits appears to have been episodic, as is the case with modern spits (Aubrey and Gaines 1982; Fox et al. 1995), in which periods of rapid progradation lasting for months or years are marked by episodes of storm erosion (Carter 1986). Spit growth increments can be identified on the upland surface of the Eastern Shore spit complex as successive sets of recurved beach ridges (Figs. 1, 16). Their bounding surfaces can be identified on GPR records as second-order reflectors (Fig. 13). The second-order reflectors are more steeply dipping than the nearly horizontal first-order reflectors but cannot be traced as far. At the Oyster pit several isolated, thin to very thin bed beds (1–10 cm thick) of gravelly sand emerge from within the horizontally stratified sand facies of the lower shoreface system at the same heights from the base as those of second-order radar reflections in the adjacent field (labeled ''G'' in Fig. 12). Although some of these gravelly beds be may be individual storm events, we infer that the thicker examples record episodes of erosion that lasted for years or decades, and constitute the bounding surfaces of spit growth increments. The increments are a high-frequency phenomenon and are not to be confused with the spit segments extending for tens of kilometers that formed during successive high stands.

DISCUSSION

Identifying Pleistocene Depositional Systems

The depositional systems (facies assemblages) of Quaternary Butlers Bluff and Accomack members can be resolved by comparing the borrow pits in which they crop out with GPR records (Fig. 12). The assemblages into which these facies are organized stand out clearly in borrow pits by

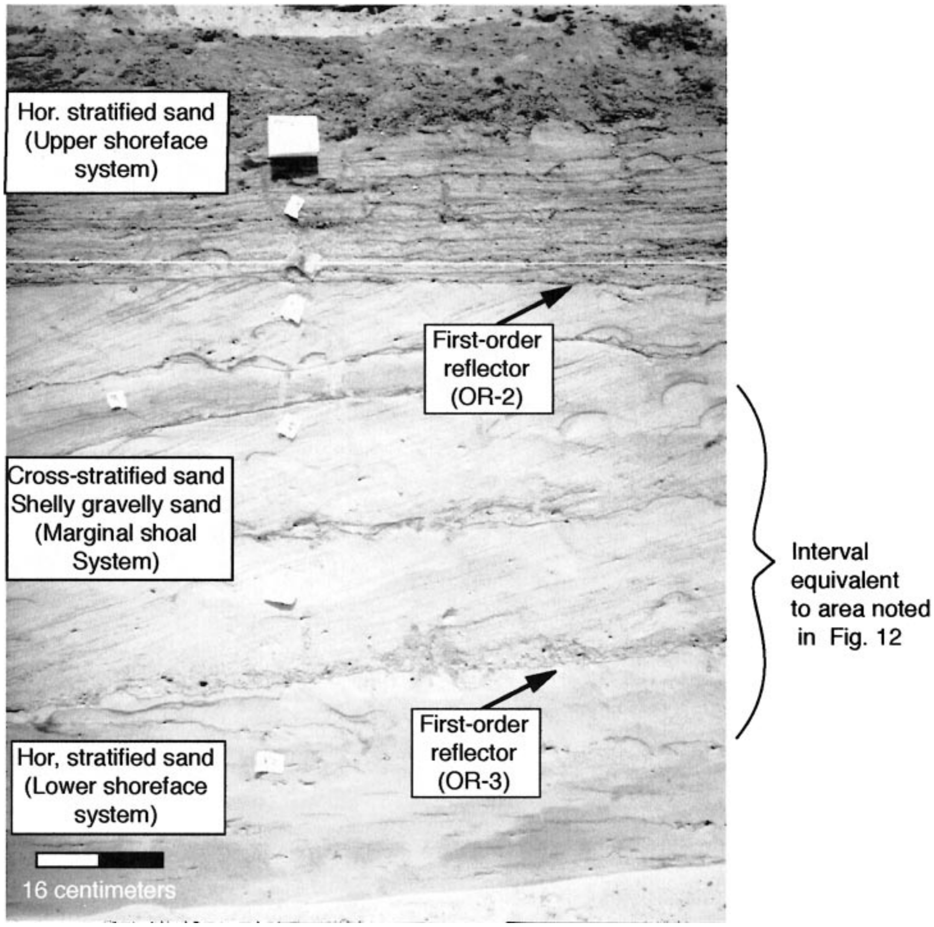

FIG. 14.—Interpreted photograph of section from Oyster borrow pit showing the contrast between the marginal shoal depositional system and the lower shoreface depositional system. Compare cross section of Pleistocene cross-strata sets with the plan view sonogram of modern bedforms, Figure 8.

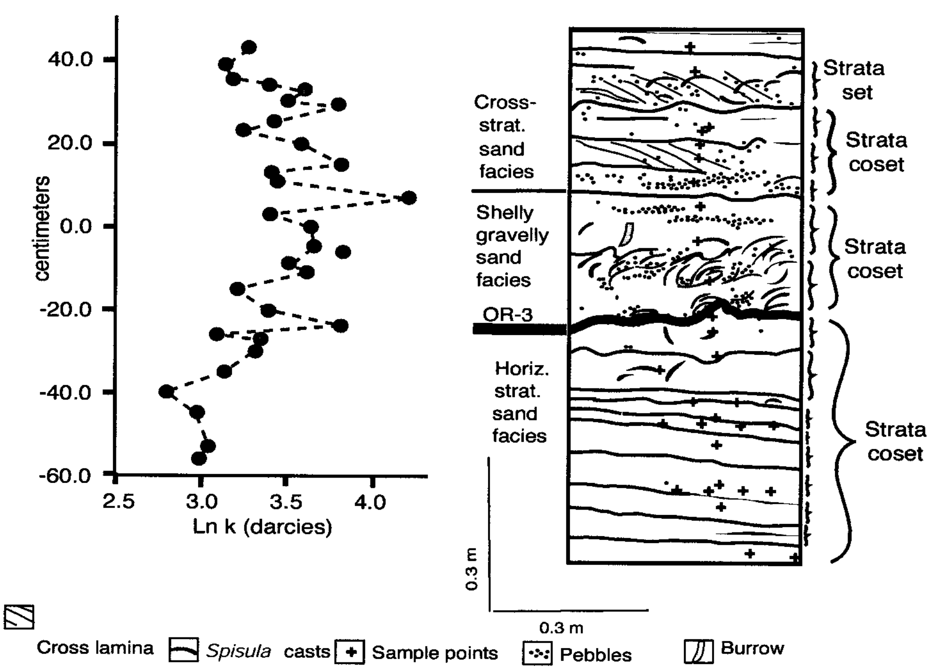

FIG. 15.—Measured section and grain size profile from the Oyster borrow pit, comparing facies nomenclature with nomenclature for stratal geometries. This section lies 10 m east of the equivalent section indicated in Figure 14, and is condensed relative to that section.

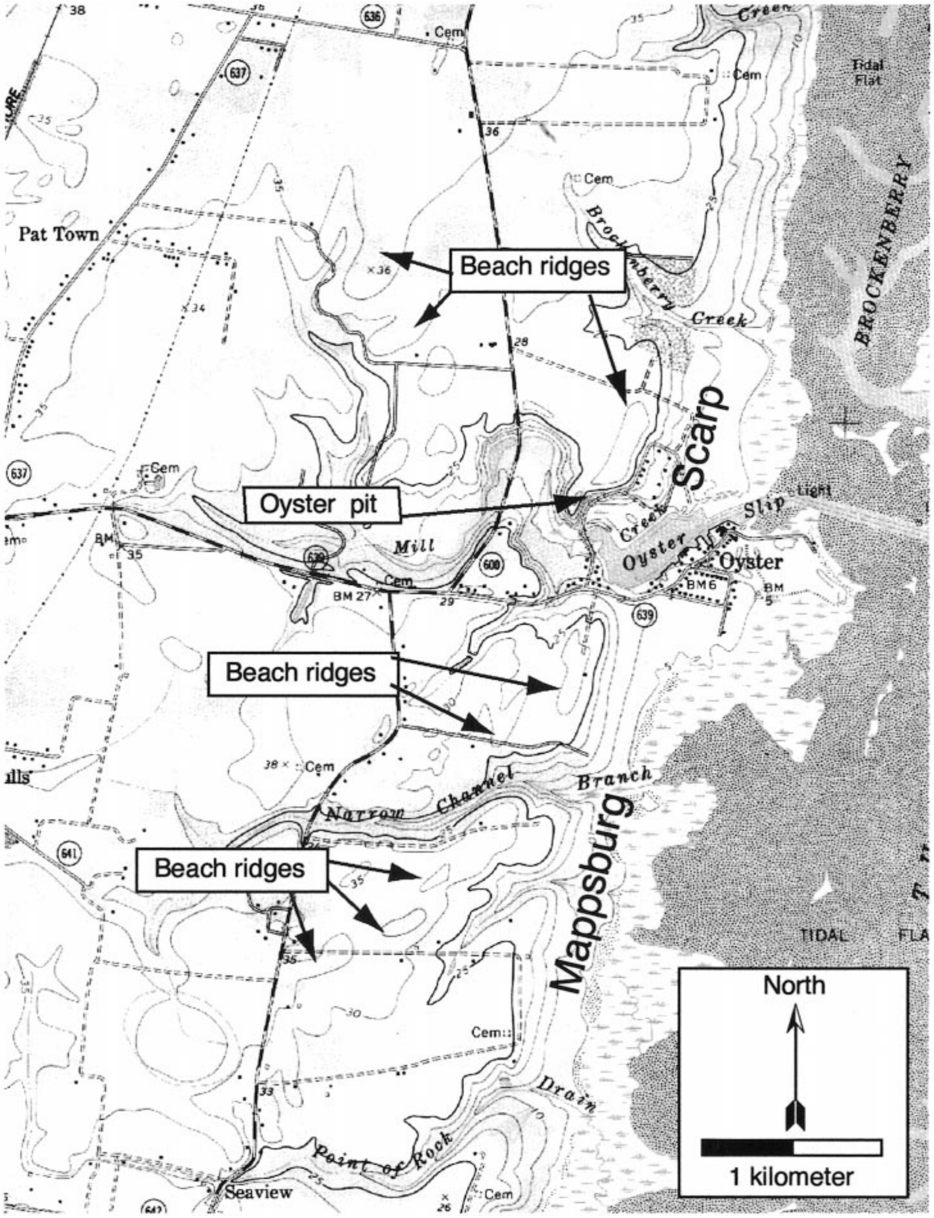

FIG. 16.—Beach ridges on the Upland Surface (surface of the Butler's Bluff Member) near Oyster, Virginia.

virtue of their sharply defined systems-bounding surfaces. Brown and Fisher (1977) first noted that the bounding surfaces of depositional systems are better defined than are the bounding surfaces of their constituent facies, but this observation has not been recognized as a basic principle. Our experience supports that of Brown and Fisher (1977); these boundaries can be traced for many kilometers beyond the borrow pits where they are exposed. Vertical facies transitions between proximal and distal facies are easily defined and identified in outcrop, but the horizontal gradients of facies change are too slight to be observed over the short dimensions of the borrow pits and do not generate the reflective interfaces as strong as those that define the assemblages.

Interpretation of Pleistocene Systems: The Holocene as a Partial Analog

The highstand Pleistocene dispersal system must have differed in significant ways from the transgressive Holocene dispersal systems portrayed in Figs. 6, 7, and 9. The Nassawadox paleospit is a continuous body nearly 70 km long. GPR records through the Mappsburg Scarp (see Fig. 1 for location) suggest that this scarp was the highstand shoreline and that it was nearly stationary during the brief time that it took for the Nassawadox spit to extend coastwise to its present length. The recurved dune ridges seen in plan view on the ''upland surface'' of the Eastern Shore (Fig. 16) indicate a ''side-slipping fishhook'' mode of coastwise propagation of the highstand shoreline. The Holocene barrier system, in contrast, consists of short (4–12 km) segments separated by deeply incised inlets and is undergoing rapid, washover-driven shoreward retrogradation. Constriction of the bay mouth by earlier completion of the Nassawadox paleospit means that present tidal currents in the bay mouth are so intense that the new ''growth area'' of the Holocene can no longer undergo subaerial progradation but bypasses its surplus sand to the reversing tidal currents of the baymouth.

Nevertheless, patterns of morphodynamical behavior are shared by the Pleistocene and Holocene dispersal systems, so that the better resolved Holocene system can be used as a ''partial analog'' for Pleistocene morphodynamics, in the sense of the term first used by Brenner (1978); See also Bouma et al. (1982). Fisherman Island and Smith Island, at the south-

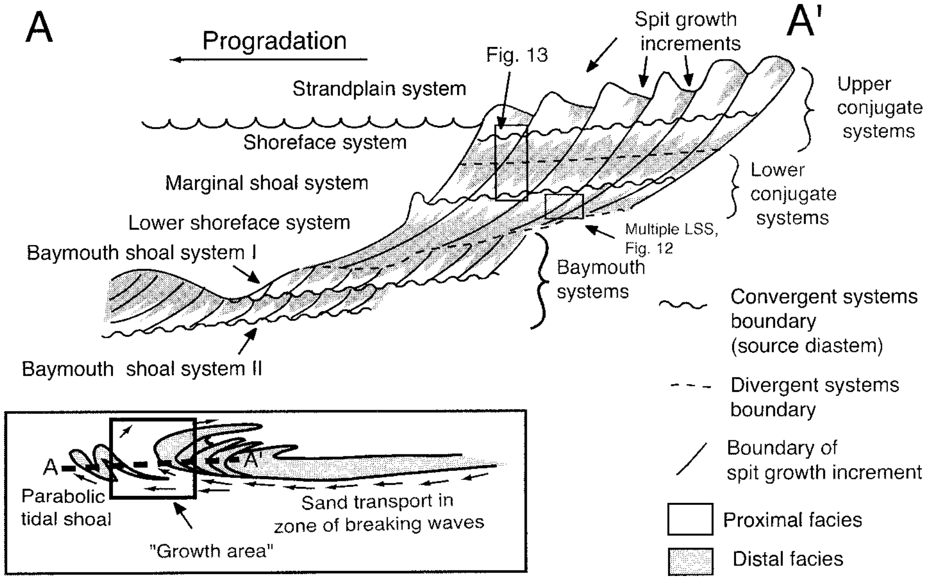

FIG. 17.—Schematic diagram illustrating the relationship between depositional systems, growth increments, and the dispersal system of the Nassawadox spit.

ern end of the Holocene Eastern Shore barrier system, both have prograding strand plains and prograding shorefaces, as the tip of the Nassawadox spit must have had. Fisherman Shoal, a marginal tidal shoal, climbs obliquely up the shoreface of Fisherman Island. Fisherman shoal is the innermost link of the of the baymouth shoal system, the ''zig-zag submarine spit'' of Ludwick (1974). As such it would be a more or less permanent feature of the bay-mouth morphology, as long as bypassing from littoral drift to submarine tidal transport occurred, and the presence of a basal layer of tidal shoals beneath the spit indicates that such bypassing was occurring even during the rapid progradation phase of the spit. We conclude that the ''growth area'' at the tip of the Nassawadox paleospit, as it overran the tidal shoals of the bay mouth must have looked much like the present southern margin of Fisherman Island.

Depositional Systems Architecture

Examination of other Mixon (1985) localities suggests that the columnar section measured in the Oyster pit and in nearby cores (Fig. 12) is characteristic of earlier highstand spit segments of Virginia's Eastern Shore Peninsula. Measured sections at Kiptopeke Beach and Abbot pit, and 10 m cores collected from the latter sites reveal that the Accomack and Nassawadox spit segments consist of as many as six stacked progradational depositional systems (Fig. 17). Each spit segment is the product of coast-parallel progradation and consists of successive systems sets (high-frequency segments, or growth increments) deposited by a small, intermittently advancing dispersal system (''growth area'' in the inset of Fig. 17). The spatial organization of dispersal environments in this southward-propagating ''growth area'' determines the resulting stratigraphy. In this model, two eroding source environments (the trough behind the marginal shoal on the middle shoreface, and the surf zone above it) are seen as key surfaces. They control sediment dispersal in the modern equivalent of the growth area (Fig. 7) and would presumably do so also in the Pleistocene equivalent.

The analysis of Holocene dispersal systems presented above suggests the following morphodynamical scenario for the deposition of the Nassawadox and Accomack paleospits segments. Littoral sand in the growth area moved during storm events, as it does on the Virginia coast today (Wright et al. 1987). Major events scoured the surf zone, cutting a new strip of the surf diastem, shunting sand seaward into rip currents, and prograding the upper shoreface as reported during observations of storm flows in the Modern Middle Atlantic Bight (Swift et al. 1985). As the storm-enhanced littoral current subsided after each event, the surf zone backfilled, covering the freshly created strip of surf diastem. Landward-asymmetrical, fair-weather motion, dominated by the landward stroke, drove sand onto the prograding beach during the ensuing fair-weather periods, as it does now on Virginia beaches (Wright et al. 1987), farther burying the surf diastem. Meanwhile, further down the shoreface, the channel behind the marginal tidal shoal and the upcurrent flank of the shoal were similarly scoured, in this case by storm-enhanced tidal currents. Sand eroded from the beach and surf zone during these events was swept obliquely across the channel and shoal, prograding the shoal and the lower shoreface below it, as sand is transported across the modern baymouth shoals (Ludwick 1975). The freshly created strip of channel-base diastem was backfilled by cross-strata sets similar to those mapped in modern tidal channels during the ensuing fair-weather period (Fig. 8).

These morphodynamical inferences lead to the model for systems architecture presented in Fig. 17. The model assumes that, as the spit-tip dispersal system prograded southward, it deposited a ''double sandwich'' of facies assemblages with clearly marked bounding surfaces (Fig. 17). The two source diastems shed sediment downslope and ahead of themselves, then, during the next event, overroded those deposits. At the end of each event, the source diastems mantled themselves in their own debris as the storm-amplified current waned. As a result each source diastem deposited two facies assemblages: one that it overrode, and one that buried the diastem. The systems were mirror-image systems (conjugate systems) in that the two proximal facies (of coarsest sediment) lay back to back. The pattern of double depositional systems (conjugate systems) does not extend down to the baymouth shoal systems that are being overrun by the coast-parallel prograding spit. Here, stacked, asymmetrical systems are separated by singly divergent source diastems.

Systems versus Sequence Architecture

Second-order bounding surfaces (Fig. 13) appear in the conceptual model as steeply dipping lines separating horizontally stratified spit increments (Fig. 17). The increments are spatially (and by inference temporally) high-frequency phenomena, and are not to be confused with the spit segments extending for tens of kilometers that formed during successive high stands. They are probably two to three orders of magnitude shorter than the highstand segments. The second-order reflectors that define the growth increments (Fig. 13) downlap onto, or toplap against, the horizontal first-order reflectors that separate facies, and a second-order reflector cutting across the upper two depositional systems locally appears to ''connect'' with a

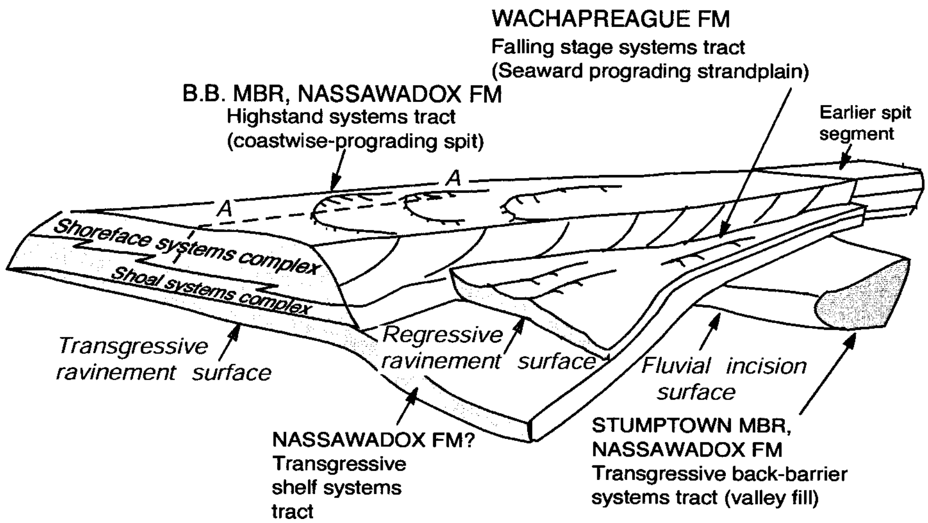

FIG. 18.—Schematic perspective view of the Nassawadox Formation, showing relationship between the depositional systems of the Butlers Bluff Member and the sequence stratigraphic elements of the Formation. Compare with Figure 1.

similar reflector cutting across the two lower systems. These cross cutting second-order reflectors presumably represent periods of erosion that halted progradation of the spit. The growth increments constitute the highest-frequency sequence stratigraphic elements present on the Eastern Shore Peninsula. They are high-frequency bed successions. They are autocyclic sequences, in that they are more likely to be due to random (chaotic) fluctuations in spit-forming processes than to sea-level fluctuations. The high-frequency repetition of a facies assemblage by autocyclic processes was first investigated by Caster (1934), who distinguished between a ''parvafacies'' within each autocyclic segment and a ''magnafacies'' as the sum of a given class of parvafacies extending through successive segments. The shoreface systems of Figure 17, as each are repeated through successive growth increments, constitute such magnafacies.

At yet larger spatial sales, the late Quaternary deposits of the Virginia Eastern Shore Peninsula are organized into apparent allocyclic (sea level–controlled) sequences at two temporal scales. This insight is based in large part on the work of Mixon (1985), who described the stratigraphic relationships that he observed with great fidelity, although he did not attempt to cast his observations into a sequence stratigraphic mold. The sequences of the Eastern Shore Quaternary inferred from Mixon's (1985) study are anomalous in that they are highly three-dimensional (Fig. 18). A single 100-kyr sequence starts off with a valley-fill deposit such as the Stumptown Member of Figure 1. Such valley-fill deposits were assigned to the lowstand systems tract in the early sequence stratigraphic literature (Van Wagoner et al. 1988). However, Dalrymple et al. (1992) and Allen and Posamentier (1993) have more recently attributed them to the transgressive systems tract. Such an interpretation seems reasonable on the Eastern Shore Peninsula, where Quaternary maximum lowstand deposits must lie at the shelf edge 180 kilometers to the east, stratigraphically lower than the lowstand valleys are incised. Consequently, we assign the Stumptown Member and other, earlier Eastern Shore valley fills to the back-barrier portion of the transgressive systems tract (back-barrier sub-tract below the ravinement surface; Thorne and Swift 1991). The transgressive shelf sub-tract presumably overlies the ravinement and is capped by the maximum flooding surface (Fig. 18). Mixon (1985) did not report a basal open-marine transgressive unit between the Butlers Bluff and Stumptown members, but the unit would be observable in the subsurface only and therefore not readily detected.

The age of the Butlers Bluff Member of the Nassawadox Formation (isotope stage 5e; See Figs. 1 and 18) and its coastwise prograding dynamic suggest that it is the 100-kyr (fourth-order) highstand systems tract of the late Pleistocene sea-level cycle (isotope stages 1–5, Fig. 4). If its history resembled that of modern spits, it would have formed quickly within this period. The Wachapreague and Joynes Neck formations, not clearly distinguished in the Eastern Shore Peninsula by either Mixon or ourselves, are capped by seaward-prograding strandplain deposits that have formed 5 meters below the highstand system (Bell Neck Strand plain, Mixon 1985). They appear to have developed during the high-frequency (fifth-order or greater) precession- and obliquity-controlled sea-level oscillations represented by isotope stages 5a–d (Fig. 4). At the temporal scale of the (fourth-order) Butlers Bluff Formation, these units constitute a falling-stage systems tract (Plint and Nummedal 2000).

SUMMARY AND CONCLUSIONS

Our primary data come from the late Pleistocene highstand deposits, but the analogous Holocene dispersal environments are sufficiently well described in the literature to permit close comparison with the Quaternary facies, so that the Quaternary deposits of the Eastern Shore Peninsula serve as a natural laboratory for uniformitarian analysis. The facies assemblages of the late Quaternary Butlers Bluff and Accomack members of the Eastern Shore Peninsula were deposited during the coast-parallel progradation of barrier spits during periods of highstand. Consequences that stem from this fact serve as keys to the uniformitarian interpretation of the resulting facies architecture. First, each successive spit unit has been produced by the coast-parallel translation of a relatively small growth area at the spit tip. Second, the present (Holocene) barrier system, more a transgressive systems set than a highstand systems set, is nevertheless a partial analog for the fossil highstand deposits, in that progradation can be observed near the southern end (Fig. 6). Third, the distal end of the Holocene barrier system appears to closely resemble the highstand growth area. Wave heights decrease rapidly near the end of the barrier system (Fisherman Island). The rate of upper-shoreface deposition is very high, and Fisherman Island is prograding into the adjacent tidal channel.

In order to initiate this analysis, we introduced a more rigorous definition of lithofacies, in which ''granulometric facies'' are defined by characteristic vertical and horizontal grain-size profiles and occur in specified relationship to their bounding surfaces. Given these relationships, the depositional systems of Quaternary Butlers Bluff and Accomack members are readily resolved by virtue of these sharply defined bounding surfaces, both in the borrow pits that expose them and on ground-penetrating radar records (Fig. 13). Three basic facies (shelly gravelly sand facies, cross-stratified sand facies, horizontally stratified sand facies) occur in varying proportions in each of five depositional systems (Fig. 12). Each facies assemblage is systematically related to a bounding surface (source diastem) that provided the sediment for the assemblage. These sharply defined bounding surfaces are first-order reflectors that are significantly more continuous than the fainter, third-order reflections of beds within the facies assemblages. The successive facies within these facies assemblages are less easily discriminated. Vertical transitions between proximal and distal facies are easily defined and identified in outcrop, but the horizontal gradients of facies change are too gentle to be observed over the short dimensions of the borrow pits and do not generate the reflective interfaces that serve to define the assemblages themselves.

The source diastems of these Pleistocene depositional systems can be compared with the eroding source environments (tidal-channel thalwegs, surf zone) in the analogous Holocene dispersal systems of the adjacent oceanic shoreline. Facies assemblages of the Nassawadox spit were organized around two coastwise-prograding erosional surfaces (source environments), the surf diastem and the channel-base diastem cut by the base of a marginal tidal channel. Each surface generated two back-to-back (conjugate) depositional systems (Fig. 17).

Progradation of the tip of the ancestral Nassawadox spit was episodic, resulting in successive sets of recurved beach ridges. The episodic process created more steeply dipping second-order reflectors that separate growth segments of the spit (Figs. 13, 17). These spit-growth increments are essentially autocyclic high-frequency sequences. They constitute the smallest scale sequence stratigraphic elements present, occurring two orders of spatial scale below the sequence architecture created by a single 120,000-yr sea-level cycle.

The manner in which facies are organized into depositional systems in the late Pleistocene highstand deposits of the Eastern Shore is specific to this setting. In particular, the ''double decker'' structure, in which two conjugate, prograding, tidal-shoal-related systems are overrun by a second conjugate set of systems (prograding shoreface–prograding strandplain) is not likely to occur in other than an estuary-mouth setting. The upper double system (prograding shoreface–prograding strandplain) is however a ubiquitous one, whose characteristics can be observed in other shallow marine deposits. More generally, these assemblages are local expressions of a ''template'' of facies and facies assemblages that can be extended to many other settings. Nummedal et al. (1993) have summarized available information concerning ''the development of multiple erosion surfaces within parasequences and sequences,'' citing many earlier observations. In addition to the surfaces described in this paper, these earlier papers describe the tidal ravinement (Allen and Posamentier 1993), bay ravinement, and fluvial erosion surface (Nummedal and Swift 1987). Nummedal et al. (1993, p. 66) offer as a new element in their paper, ''the explicit modeling of generation and loss of accommodation space in response to migrations of fluvial and shoreface equilibrium profiles.'' We support the inference of Nummedal et al. (1993), who conclude that intrasequence surfaces are systematically positioned within the evolving sequence, and offer as a new element in this paper, evidence that in addition they control the arrangement and character of the intervening facies assemblages.

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